REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10 May 96	FINAL TECHNICAL REPORT 1 Feb 95 to 31 Mar 96

4. TITLE AND SUBTITLE OF REPORT

Graduate Course in Optical Oceanography

5. FUNDING NUMBERS

N00014-95-1-0473

6. AUTHOR(S)

Patricia G. Hull

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Tennessee State University
3500 John Merritt Boulevard
Nashville, TN 37209-1561

8. PERFORMING ORGANIZATION REPORT NUMBER:

none

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research, Code 252B-BDG
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER:

11. SUPPLEMENTARY NOTES:

Scientific Officer: Steve Ackleson, Code 323

12a. DISTRIBUTION AVAILABILITY STATEMENT

Unlimited

12b. DISTRIBUTION CODE

19960522 022

13. ABSTRACT (Maximum 200 words)

A 5-week summer graduate-level exercise in Optical Oceanography at the University of Washington's Friday Harbor Laboratories (FHL) was offered in summer 1995. The focus of this course was radiative transfer in the ocean with an emphasis on Case II waters. An underlying philosophy of the exercise was that a mechanistic understanding of radiative transfer in the ocean must include biological terms. The exercise was an intensive, hands-on experience for 15 students plus faculty, combining theory, measurement, and modeling in the unique coastal and estuarine settings of the San Juan Islands and Strait of Juan de Fuca. The course was a cooperative effort of Tennessee State University and University of Washington.

14. SUBJECT TERMS	15. NUMBER OF PAGES: 11
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified	unclassified	none

Final Technical Report

ONR Grant N00014-95-1-0473

"Graduate Course in Optical Oceanography"

Principal Investigator: Patricia G. Hull

Tennessee State University

Department of Physics, Mathematics and Computer Science

February 1, 1995 to March 31, 1996

Graduate Course in Optical Oceanography

Mary Jane Perry & Norman McCormick
Course Coordinators
University of Washington
Seattle, Washington 98195

Patricia G. Hull (PI)
Tennessee State University
Nashville, TN 37209

ABSTRACT

A 5-week summer graduate-level exercise in Optical Oceanography at the University of Washington's Friday Harbor Laboratories (FHL) was offered in summer 1995. The focus of this course was radiative transfer in the ocean with an emphasis on Case II waters. An underlying philosophy of the exercise was that a mechanistic understanding of radiative transfer in the ocean must include biological terms. The exercise was an intensive, hands-on experience for 15 students plus faculty, combining theory, measurement, and modeling in the unique coastal and estuarine settings of the San Juan Islands and Strait of Juan de Fuca. The course was a cooperative effort of Tennessee State University and University of Washington.

GOAL: The course goal was to provide an opportunity for graduate students to learn the fundamentals of optical oceanography in a coastal/estuarine environment. Nine semester hours of graduate credit for the course was given by University of Washington. The course provided TSU students and students from other non-oceanographic institutions a unique opportunity to participate in an optical oceanography course in a coastal setting.

APPROACH: Graduate students from all sub disciplines of oceanography were encouraged to apply. In addition, course announcements were mailed to non-oceanographic institutions with graduate programs in basic and applied optics programs. The success of this strategy is evidenced by the quality and diversity of the forty-eight students who applied. Appendix 1 lists the fifteen students chosen for the course as well as the other students who applied but were not selected to participate. The course strived for a balance among optical theory, measurement, and models. Field measurements, made by the students, were incorporated into optical models and used as teaching tools to explore the errors and limitations of both. The close proximity of a diversity of coastal/estuarine water types enabled students to develop an appreciation for the special research issues associated with Case II waters, in addition to the more general issues addressed in the majority of marine optics publications which focus on Case I-type waters. The biological foci were: 1) the role of phytoplankton, other biologics and derived products on inherent optical properties, and 2) the extraction of biological signals from inversion of radiative transfer equations.

RESULTS: The course was taught between 17 July and 19 August 1995 at Friday Harbor Laboratories. An entire teaching laboratory was dedicated to the Optical Oceanography course. The main components of the course were: (1) lectures; (2) readings from course texts; (3) formal (i.e., instructor-directed) field measurements and modeling exercises, with an emphasis on integration of field measurements with models and theory; (4) student projects, concluding with written and oral reports; and (5) weekly critical discussions of key papers. See Appendix 2 for a detailed course schedule.

Lectures: The topics covered in the lectures included: the nature of light; radiometric terms; underlying principles and limitations of current radiometric measurements; optical properties of water including inherent and apparent optical properties; role of phytoplankton, dissolved organic material, and inorganic and biologically-derived particles in determining inherent optical properties; measurement of inherent optical properties; derivation of the radiative transfer equations; air-water interface effects; relationship between inherent and apparent optical properties; inverse methods including remote sensing, retrieval of phytoplankton properties, and effects of fluorescence. Thirty-nine seminar-style lectures were delivered by the course coordinators, M.J. Perry, and N.J. McCormick (U. of Washington), guest lecturers, C.S. Roesler (U. of Connecticut), K.D. Carder (U. of South Florida), C.D. Mobley (SRI International), and P.G. Hull (Tennessee State U), and opportunistic guest lecturers, T. Cucci (Bigelow Labs) and D. Coder (U. of Washington), R. Desiderio (Oregon State U.), S. Ackleson (ONR), and M.E. Culver (U. of Washington). On Saturday, August 5, an all-day workshop on flow cytometry with "hands on" work with the flow cytometer was given by Terri Cucci and Dave Coder.

Texts: The texts from which readings were assigned to augment the lectures, and to enable the student to continue learning after the termination of the course, were:

Light and photosynthesis in Aquatic Ecosystems, second edition. (1994) J. T. O. Kirk. Cambridge University Press.

Light and Water: Radiative Transfer in Natural Waters. (1994) C. Mobley. Academic Press.

Ocean Optics. (1994) R. W. Spinrad, K. L. Carder, and M. J. Perry (editors) Oxford Univ. Press, N. Y.

Laboratories: The formal "laboratory" portions of the course consisted of instructor-directed field measurements during weeks one and two, and instructor-directed modeling exercises during weeks three and four. For the field measurement laboratories, the class divided into small groups and worked with an instructor on specific measurements. During the first two weeks, each student had the opportunity to work with all the equipment. The measurements included: in-water and above-water radiometry with different instruments; above-water reflectance; spectrophotometry for absorption coefficients of dissolved organics, phytoplankton and "detritus"; and ancillary data (temperature, etc.). In addition to the equipment belonging to the laboratory, the guest lecturers, Collin Roesler and Kendall Carder provided some of their own equipment. Roesler compiled a helpful a table of the instruments available to the students, the quantities each instrument measured and

the quantities that could be derived from the measurements. See Appendix 3 for this table. During the second week (after the students gained experience with the measurements), data was collected in an organized sampling experiment to: (1) attempt optical closure and (2) provide Case II-water data to be used in running Mobley's models. The collection of computers we provided to facilitate data analysis included PCs and Macintosh computers from the instructors' own laboratories, three rental SPARC-2 workstations, and three rental power Macintoshes.

During weeks three and four, the formal laboratory exercises were hands-on work with Mobley's radiative transfer models, using data collected during week two as input parameters and output validation. The modeling work provided students the opportunity to attempt integration of field measurements with models. Only the SPARC-2 workstations were able to run Mobley's "Hydrolite" computer code, however, several of the other computers were networked with the SPARC-2's in order to provide addition access by students.

Technical assistance was provided from the beginning of the course to its completion by David English and Mary Kay Talbot. David's assistance in procuring the computers, obtaining special licencing of software for the computers, teaching the students to safely use the field equipment, assistance in data analysis, and repair of field equipment was invaluable.

Student projects: In week three, each student selected a topic for more detailed, in-depth study. The student project was one of the most important components of the FHL course, allowing the student to integrate the information to which she or he had been exposed. On the last day of class, the students presented their results as formal oral talks and submit written reports. The written reports are available in the FHL library. Appendix 4 is a listing of the topics of the student reports.

Critical discussions of key papers: The other important component of the FHL course was the discussion of papers. Saturday was devoted to an in-depth discussion of a key paper. These half-day or longer discussions followed a proven formula, called "Learning Through Discussion," that we have found crystallizes the students' integration of information. These discussions were one of the most rewarding experiences for the instructors as we literally watch the "lights" go on.

STUDENT EVALUATIONS: At the University of Washington, it is routine for students to evaluate instructors for a course at the end of the semester by filling out an evaluation questionnaire for each of the course lecturers. These evaluations were very positive and generally expressed satisfaction (more often enthusiasm) for the quality of the instruction. The most important evaluation of the course, however, was in the form of a round-table discussion the last evening of the course. We asked the students to be completely candid and offer any criticisms, constructive or otherwise, they had of the course. The students generally expressed overall satisfaction with the course. However, one problem was expressed by almost every student. We needed more computing power! The amount of data the students were able to gather was overwhelming. It often took hours downloading the data from a single instrument and the files were much too large for the desktop computers some

of the students brought with them. It was an unusual case of too much data to process. Should this course be taught again, it would be of utmost importance to devote time to develop a plan for better data management and analysis.

STATISTICS

0 Papers published, referred journals
0 Papers submitted, refereed journals
0 Books or chapters published, refereed publication
0 Books or chapters submitted, refereed publication
0 Invited presentations
0 Contributed presentations
0 Technical reports and papers, non-refereed journals
3 Undergraduate students supported
0 Graduate students supported
0 Post-docs supported
0 Other professional personnel supported

EEO/MINORITY SUPPORT

2 Minority undergraduate students supported
5 Female grad students
2 Minority grad students
0 Asian grad students
0 Female post-docs
0 Minority post-docs
0 Asian post-docs

Patents and awards 0

APPENDIX 1.

STUDENTS PARTICIPATING IN THE 1995 OPTICAL OCEANOGRAPHY COURSE AT THE UNIVERSITY OF WASHINGTON FRIDAY HARBOR LABS.

1. Emmunuel Boss
   University of Washington
2. Christopher Cantrell
   University of South Florida
3. Angel Dieppa
   University of Puerto Rico
   at Mayaguez
4. Sonja C. Gallegos
   Naval Research Lab Code 7240
   Stennis Space Center
5. Rebecca L. Hansing
   Oregon State University
6. Miguel Hayes
   Tennessee State University
7. Omari K. Jones
   Tennessee State University
8. James V. Koziana
   Old Dominion University
9. Robert A. Leathers
   University of Washington
10. Vilayakumar Manghnani
    North Carolina State University
11. Robert J. Parada Jr.
    Universiy of Arizona
12. Naomi S. Parker
    University of Tennessee
13. Anne A. Petrenko
    University of Southern California
14. Anthony J. Vital
    Tennessee State University
15. Gregory M. Weiss
    University of New Hampshire

STUDENTS WHO APPLIED BUT DID NOT PARTICIPATE IN THE 1995 OPTICAL OCEANOGRAPHY COURSE.

1. Raul Aguirre-Gomez
   University of Southampton
2. Edwin Alfonso
   University of Puerto at Mayaguez
3. Jasmine S. Bartlett
   Dalhousie University
4. Titus L. Berry
   Tennessee State University
5. Francisco P. Chavez
   Monteray Bay Aquarium
   Research Institution
6. Daniela T. Necsolu
   University of Bucharest
7. Dmitry M. Onoshko
   Belorussian State University
8. Deborah Parrilla
   University of Puerto Rico at
   Mayaguez
9. Kelly L. Rankin
   Steven Institute of Technology
10. Susan K. Runco
    Johnson Space Center

11. Aurea M. Clotti
Dalhousie University

12. Trine Dale
University of Bergen

13. Piotr. J. Fiatau
University of California, San Diego

14. Jan S. Gunderson
Texas A & M University

15. David Illuz
Bar-Illan University

16. Viatcheslav A. Klenov
University of South Florida

17. Mark V. Kovaltchouk
Belorussian State University

18. Adam B. Kusta
College of Charleston

19. Igor A. Majevich
Belorussian State University

20. Sergey V. Matloshkov
Belorussian State University

21. Tiffany Moisan
University of California, San Diego

22. Lisa Moore
Massachusetts Institute of Technology

23. Roar Sandvik
University of Trondheim

24. Yuta Sauya
Tokai University

25. Marek D. Schnee
Institute of Oceanology
Polish Academy of Sciences

26. Jill N. Schwarz
University of Southampton

27. James S. Stewart
University of Colorado

28. Fredrick Stahr
University of Washington

29. Theodore J. Swift
University of California at Davis

30. Ajlt Subramaniam
State University of New York at
Stony Brook

31. Dan L. Woodruff
University of North Carolina

32. Alexey K. Yasakov
Belorussian State University

33. Vimel Zhou
Vrije University

APPENDIX 2: OPTICAL OCEANOGRAPHY COURSE SCHEDULE, 1995

Week I

Monday, 17 July	
Welcome, introductions, goals	
Radiometry	McCormick
Tuesday, 18 July	
Radiometry theory	McCormick
Instrumentation and real-world radiometric measurement	Carder
Lab - instrumentation, calibration, units, geometry	
Wednesday, 19 July	
Apparent Optical Properties (AOPs) - terms	Roesler
Apparent Optical Properties (AOPs) - measurement	Carder
Lab: in-water radiometric measurements of PAR (cosine and 4p), Ed, Eu, transmission; plot measured parameters; discuss units and artifacts; calculate AOPs	
Thursday, 20 July	
Inherent Optical Properties (IOPs) -- introduction and terms	McCormick
IOPs -- phytoplankton	Perry
Lab: rotation -- 4 groups	
I. AOPs (Nugget)	Carder
II. IOPs (Nugget)	Roesler & English
III. absorption (lab)	Talbot
IV. particles and chlorophyll *a* analysis	Perry
Friday, 21 July	
IOPs -- Phytoplankton pigments	Perry
IOPs -- measurements of absorption	Roesler
Lab: Continuation of lab rotation	
Saturday, 22 July	
Discussion paper #1	
Spinrad, Carder and Perry (eds.) 1994. Chapter 4, Kishino "Interrelationship between light and phytoplankton in the sea."	

Week II

Monday, 24 July	
IOPs -- scattering physics (phase function, volume scattering function., Petzold)	McCormick
IOPs -- particle scattering and particle size distribution	Roesler
Lab: Continuation of lab rotation	
Tuesday, 25 July	
IOPs -- phytoplankton photoadaptation, photon adsorption, photosynthesis, and quantum yield	Perry
IOPs -- particle optical efficiency factors	Roesler
Lab: Continuation of lab rotation	
Wednesday, 26 July	
Radiative Transfer	McCormick
Remote Sensing	Carder
Absorption methods	Roesler
Lab: analysis of field data	

Thursday, 27 July

Remote Sensing	Carder
Radiative transfer & asymptotic radiance distributions	McCormick
Student project: scope, suggestions, discussion	
Lab: continue analysis of field data	

Friday, 28 July

Remote Sensing	Carder
Model for spatial dependence of AOPa to obtain IOPs	McCormick
Project: group meetings	
Lab: continue analysis of field data	

Saturday, 29 July

Quantum mechanics of absorption and fluorescence
Guest lecture by Dr. Russ Desiderio, OSU
Discussion paper #2
Spinrad, Carder and Perry (eds.) 1994. Chapter 5, Morel.
"Optics from the single cell to the mesoscale"

Week III

Monday, 31 July

Introduction and overview	Mobley
Overview of Hydrolight	Mobley
Nugget trio to Cattle Pass/ Straits of Juan de Fuca	
Lab: Hydrolight	

Tuesday, 1 August

Photosynthesis	Perry
A closer look at Hydrolight	Mobley
Lab: Hydrolight /	
Field data analysis	
Projects	

Wednesday, 2 August

Inverse radiative transfer methods	McCormick
Primary production and florescence	Perry
Lab: Hydrolight	
Field data analysis	
Projects	

Thursday, 3 August

Derivation of phytoplankton absorption from reflectance	Roesler
Nugget trip to East Sound	
Lab: Hydrolight /	
Field data analysis	
Projects	

Friday, 4 August

Analytic Solutions	Mobley

Interpretation and measurement of phytoplankton fluorescence;
Guest lecture by Mary Culver, UW
Flow cytometric measurement of phytoplankton optics;
Guest lecture by Steven Ackleson, ONR
Funding opportunities for marine optics
Guests: Steve Ackleson, ONR
Larry Clark, NSF

Saturday, 5 August

Flow cytometry workshop (all-day)

Introduction to flow cytometry

Guest lectures: Terri Cucci/Bigelow Labs
Dave Coder/UW

Lab: Hands-on work with the flow cytometer

Week IV

Monday, 7 August

Underwater visibility and imaging	Mobley
Paper discussion #3	
Falkowski and Kolber, 1993, Estimation of phytoplankton photosynthesis by active fluorescence, ICES maar. Sci. Symp. 197: 92-103	
Lab: student projects and Hydrolight	

Tuesday, 8 August

Inverse methods -- source estimation	McCormick
Lab: student projects and Hydrolight	

Wednesday, 9 August

Modeling phytoplankton production growth	Mobley
Lab: student projects and Hydrolight	

Thursday, 10 August

Modeling phytoplankton production growth	Perry
Lab: student projects and Hydrolight	

Friday, 11 August

Measurement of scattering	Mobley
Lab: student projects and Hydrolight	

Saturday, 12 August

Discussion paper #4 J.J. Cullen and M.R. Lewis (1995) "Biological processes and optical measurements near the sea surface: Some issues relevant to remote sensing: J. Geophys. Res. 100: 13255-13266

Week V

Monday, 14 August

Polarization	Hull
Demos	
Lab: student projects	

Tuesday, 15 August

Measurement of polarized light	Hull
Demos	
Course evaluation and Round Table discussion	
Lab: student projects	

Wednesday, 16 August

Optional discussion paper #5: W. S. Bickel and W.M. Bailey (1995) "Stokes vectors, Mueller matrices, and polarized scattered light." Am. J. Phys. 53: 468 - 478

Lab: student projects

Thursday, 17 August

Student presentations

Friday, 18 August

Student presentations and final reports

APPENDIX 3. Instruments used and measurements made during the course. Table prepared by Collin Roesler.

In Situ Profiling Measurements

Instrument	Measured Quantities	Derived Quantities
PAR, PAR_o sensors	$E_d(z)$, $E_u(z)$, $E_{od}(z)$, $E_{ou}(z)$	$K_d(z)$, $K_u(z)$, $K(z)$, $K_{od}(z)$ $K_{ou}(z)$, $K_o(z)$, $\mu(z)$, $\mu_d(z)$, $\mu_u(z)$, $R(z)$
LiCor 1800 Spectroradiometer	$E_d(\lambda,z)$, $E_u(\lambda,z)$, λ=300–750 nm	$K_d(\lambda,z)$, $K_u(\lambda,z)$, $K(\lambda,z)$, $R(\lambda,z)$
Spectrix	$L_u(\lambda,0+,\theta,\phi)$, $E_d(\lambda,0+)$, λ=350-900 nm	$R_{RS}(\lambda,0+)$
Wetlabs AC-9	$a_{T-w}(\lambda,z)$, $c_{T-w}(\lambda,z)$, λ=412, 440, 488, 510, 532, 555, 650, 676, 712	$b_{T-w}(\lambda,z)$, chl(z)
LISST	$\beta(\theta, z, \lambda= 670)$, $\theta = 0.05° - 5°$ c(670)	particle size distribution (d = 5 to 500 μm)

Water Sample Analyses

Instrument	Measured Quantities	Derived Quantities
Spectrophotometer	$OD_p(\lambda)$, $OD_d(\lambda)$, $OD_g(\lambda)$	$a_p(\lambda)$, $a_d(\lambda)$, $a_\phi(\lambda)$, $a_g(\lambda)$
Turner Fluorometer	Chlorophyll fluorescence	extracted chl and pheo concentrations; in vivo chlorophyll concentrations
Spectrix	$L(\lambda,0+,\theta,\phi)$; λ=350-900 nm	$R(\lambda)$ and $a(\lambda)$ of a solid sample such as an algal frond or filter pad
EPI Fluorescence Microscope	Fluorescent particle counts and identification	same
LISST	$\beta(\theta, z, \lambda= 670)$, $\theta = 0.05° - 5°$ c(670)	particle size distribution (d = 5 to 500 μm)
Galai CIS100	Particle Identification; time course of laser across particle	Particle concentration and size distribution
Flow Cytometer	Red and orange fluorescence, side and backscattering of individual particles	Size, index of refraction, and fluorescence of individual algal cells

APPENDIX 4. OPTICAL OCEANOGRAPHY STUDENT PROJECTS

Emmanual Boss
Using Hydrolight to test the CZCS algorithm or is case 2 water solved?

Christopher Cattrall
Measuring the total absorption coefficient by pad absorption, transmissometer, and remote sensing reflectance: comparison of results

Angel Dieppa
Retrieval of absorption coefficients from spectroradiametric and non-spectrally dependent PAR data using Gershun's equation

Sonia Gallegos
Influences of the tidal cycle on the remote sensing reflectance

Rebecca Hansing
The rate of approach to asymptotic light regimes for highly scattering waters, Puget Sound, Washington

Miguel Hayes
Comparison of analytical calculations with the Mie model and Henyey-Greenstein phase functions

Omari Jones
Tracking of the population growth of the *Isochrysis galbana* species of phytoplankton through flow cytometry

James Koziana
Estimates of a marine light field using a simplified 1-D bio-optical model

Robert Leathers
Sensitivity of the simulated underwater light field to corrections for scattering error in AC-9 absorption measurements

Vijay Manghnani
Testing assumptions in existing inversion models for the remotely sensed reflectance and derivation of a semi-empirical model using Hydrolight

Robert Parada
Effects of bottom depth and varying illumination conditions on remote sensing reflectance from shallow coastal waters

Naomi Parker
Effects of marine algae on remote sensing reflectance

Anne Petrenko
Effects of phase function on AOPs and remote sensing reflectance

Anthony Vital
Effects of particle size at small angles on the beam spread function

Gregory Weiss
Spatial variability and scale in measuring optical properties